Structure of Glow Discharge

Most schools have more fluorescent bulbs than TOKAMAKS

The glow discharge owes its name to the fact that plasma is luminous. The glow can be produced by applying a potential difference between two electrodes in a gas. The potential drops rapidly close to the cathode, vary slowly in the plasma, and change again close to the anode. The electric fields in the system are restricted to sheaths at each of the electrodes. The sheath fields are such as to repel electrons trying to reach either electrode. Electrons originating at the cathode will be accelerated, collide, transfer energy, leave by diffusion and recombination, slow by the anode and get transferred into the outside circuit. The luminous glow is produced because the electrons have enough energy to generate visible light by excitation collisions. Since there is a continuous loss of electrons, there must be an equal degree of ionization going on to maintain the steady state. The energy is being continuously transferred out of the discharge and hence the energy balance must be satisfied also. Simplistically, the electrons absorb energy from the field, accelerate, ionize some atoms, and the process becomes continuous. Additional electrons are produced by secondary emission from the cathode. These are very important to maintaining a sustainable discharge. Three basic regions are described below, the cathode region, the glow regions, and the anode region.

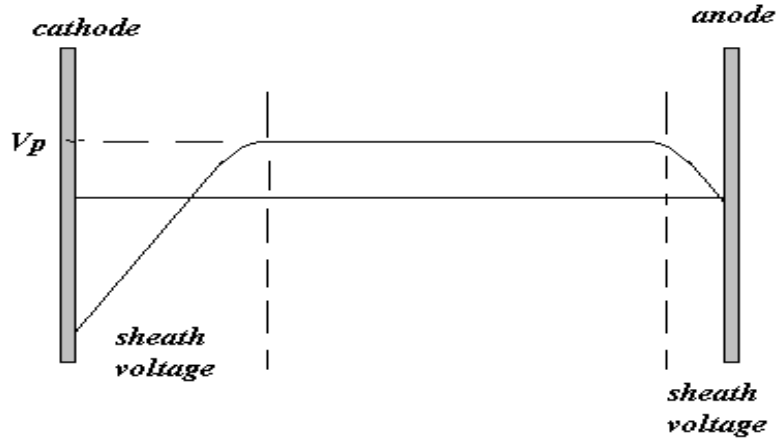
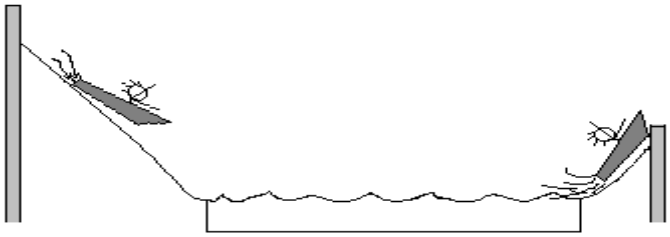


Fig. 1 Voltage distribution in a dc glow discharge process.

An electron riding through the discharge tube: an amusement park analogy.



Several practically important configurations of glow discharge are shown below. The fluorescent light bulb type of an arrangement is an evacuated glass tube with circular disk electrodes at either end, connected to a high voltage DC power supply. Once a sustainable DC glow discharge is established, it has a striking appearance of alternating light and dark spaces. The structure of a typical low pressure glow discharge is shown in Figure 2.

These structures were first observed in 1830's by Michael Faraday. The structures appear over a wide range of operating conditions. A characteristic set of operating conditions for the normal discharge shown above might be a voltage of about 1 kV, a total current of about 0.1 A, and air or Ar gas at .5 Torr.

The description of various structures starts at the cathode and proceeds toward the anode.

Cathode – An electrical conductor with a secondary emission coefficient γ that is very important for the operation of the discharge tube.

Aston Dark Space – A thin region to the right of the cathode with a strong electric field. The electrons are accelerated through this space away from the cathode. This region has a negative space charge, meaning that stray initial electrons together with the secondary electrons from the cathode outnumber the ions in this region. The electrons are too low density and/or energy to excite the gas, so it appears dark.

Cathode Glow – The next structure to the right of Aston dark space. Here the electrons are energetic enough to excite the neutral atoms they collide with. (In air this region is usually reddish due to the emissions by the excited atoms sputtered off the cathode surface, or the positive ions moving toward the cathode.) The cathode glow has a relatively high ion density. The axial length of the cathode glow depends on the type of gas and the pressure. The cathode glow sometimes clings to the cathode and masks the Aston dark space.

Cathode (Crooks, Hittorf) dark space - Relatively dark region to the right of the cathode glow that has moderate electric field, a positive space charge and a relatively high ion density.

Negative Glow – The brightest intensity of the entire discharge. The negative glow has relatively low electric field, long, compared to the cathode glow and is the most intense on the cathode side. Electrons carry almost the entire current in the negative glow region. Electrons that have been accelerated in the cathode region to high speeds produce ionization, and slower electrons that have had inelastic collisions already produce excitations. These slower electrons are responsible for the negative glow. The electron number density in the negative glow is about 10^{16} electrons/m^3. As these electrons slow down, energy for excitation is no longer available and Faraday dark space begins.

<u>Cathode Region.</u> – Most of the voltage drop across the discharge tube occurs between the cathode and the negative glow. The length of the cathode region, from the cathode surface to the boundary of the negative glow is dc. The voltage drop here is Vc volts. Most of the power is dissipated in this region. The electrons are accelerated in this region to energies high enough to produce ionization and avalanching in the negative glow, and in the regions to the right of the right of the negative glow.

A low pressure discharge will adjust the axial length of its cathode region, d_c, so that the minimum value of the product d_{cp} is established,

$$d_{cp} \sim (dp)_{min}$$

This product is the Paschen minimum. At the Paschen minimum the discharge maintains itself with a minimum cathode fall voltage V_c and minimum power dissipation. In the normal glow discharge, the current density flowing to the cathode remains approximately constant as the total current varies, as the total area of contact with the cathode increases with the total current. Typical values in air at a pressure of 1 Torr might be a current density of 0.3 mA/cvm2, dc approximately 0.5 cm, and cathode fall voltage between 100 to 300 V.

Faraday dark space – The electron energy is low in this region. The electron number density decreases by recombination and diffusion to the walls, the net space charge is very low, and the axial electric field is small.

Positive Column – Quasi-neutral, small electric field, typically 1 V/cm. The electric field is just large enough to maintain the degree of ionization at its cathode end. The electron number density is about 10^{15} to 10^{16} electrons/m^3 in the positive column, and the electron temperature of 1 to 2 eV. In air the positive column plasma is pinkish blue. As the length of the discharge tube is increased at constant pressure, the length of the cathode structures remains constant (pd_c = constant), and the positive column lengthens. The positive column is a long, uniform glow, except when standing or moving striations are triggered spontaneously, or ionization waves are triggered by a disturbance.

Anode glow – Slightly brighter than the positive column, and not always present. This is the boundary of the anode sheath.

Anode dark space – The space between the anode glow and the anode itself is the anode sheath. It has negative space charge due to electrons traveling from the positive column to the anode. There is a higher electric field than the positive column. The anode pulls electrons out of the positive column and acts like a Langmuir probe in electron saturation.

Striations – Moving or standing striations are traveling waves or stationary perturbations in the electron number density which occur in partially ionized gases. In their usual form moving striations are propagating luminous bands which appear in positive columns. Standing striations can be easily photographed. Many apparently homogeneous partially ionized gasses in reality have moving striations.

Abnormal Glow Discharges

In the normal glow increasing current (over a range of 2 – 3 magnitudes) in a discharge tube leads to a very slow change in voltage. As mentioned above, the current density to the cathode remains constant, and the current increases by covering a greater cathode region. Once the whole surface of the cathode is covered by the discharge, the only way the total current can increase further is to drive more current through the cathode by applying more voltage, and moving away from the Paschen minimum. The cathode fall potential increases rapidly, and the dark space shrinks. Except for being more intensely luminous, the abnormal glow discharge appears very similar to the normal discharge. Sometimes the structures near the cathode blend into one another providing more or less uniform glow. As the current and voltage increase, the cathode current density also increases, ultimately heating the cathode and causing incandescence and thermionic emission. Once the cathode is hot enough to emit electrons thermionically, the discharge will change to an arc regime.

Obstructed Discharges

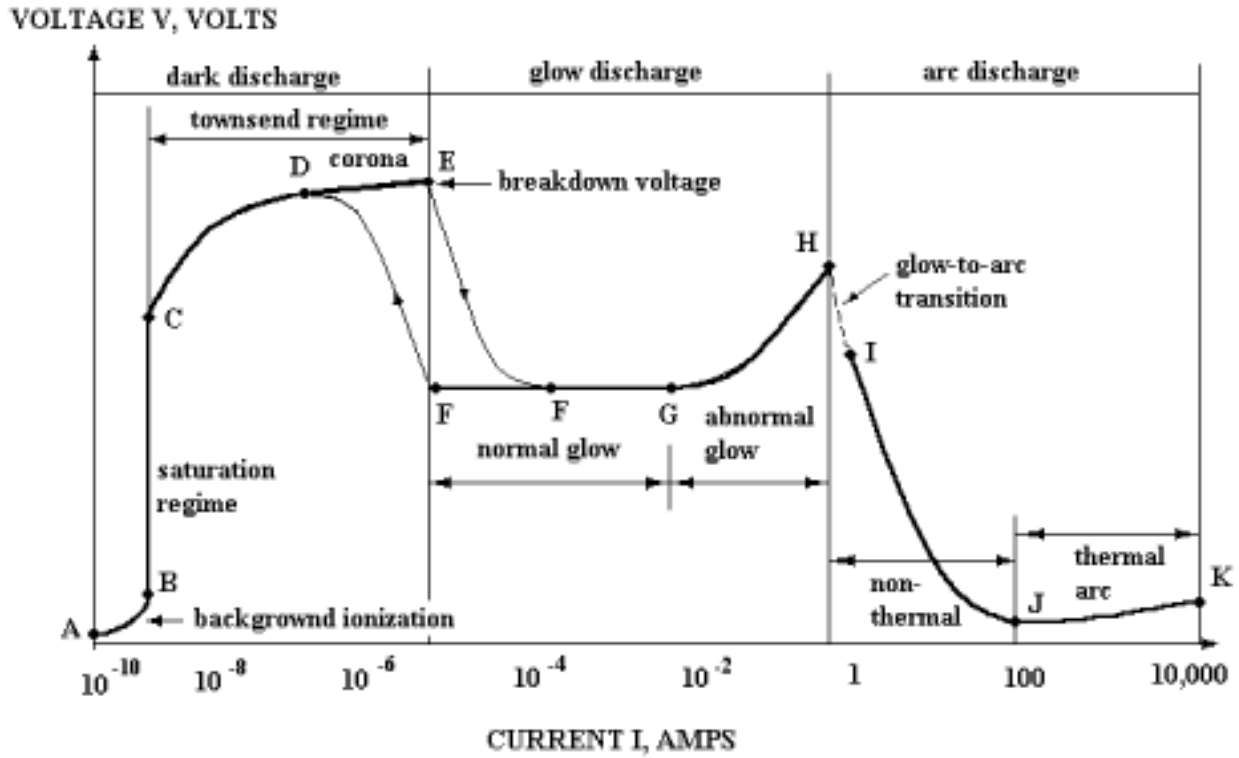
If the length L of the glow discharge is less than the Paschen minimum d_c at the Paschen minimum, the cathode fall voltage rises above the Paschen minimum value V_{cmin}. The anode glow disappears when the anode reaches the negative glow.

There are various other types of glow discharge: examples include spray discharge, high-pressure glow discharge, hollow cathode discharge.

Structure of Glow Discharge – Continued

Voltage – Current Characteristic

The main characteristics of the discharge such as the breakdown voltage, the voltage current characteristic, structure of the discharge depend on the geometry of the electrodes and the vessel, the gas used, the electrode material. By adjusting the ballast resistor in the circuit diagram, we can sweep out a voltage current characteristic that is highly nonlinear.



Three general regions ca be identified on the diagram above, the dark discharge region, the glow discharge, and the arc discharge. Each of these general regions encompasses many interesting phenomena.

Dark Discharge

The regime between A and E on the voltage-current characteristic is termed a dark discharge because, except for corona discharges and the breakdown itself, the discharge remains invisible to the eye.

A – B During the ***background ionization*** stage of the process the electric field applied along the axis of the discharge tube sweeps out the ions and electrons created by ionization from background radiation. Background radiation from cosmic rays, radioactive minerals, or other sources, produces a constant and measurable degree of ionization in air at atmospheric pressure.

The ions and electrons migrate to the electrodes in the applied electric field producing a weak electric current. Increasing voltage sweeps out an increasing fraction of these ions and electrons.

B – C If the voltage between the electrodes is increased far enough, eventually all the available electrons and ions are swept away, and the current saturates. In the ***saturation region***, the current remain constant while the voltage is increased. This current depends linearly on the radiation source strength, a regime useful in some radiation counters.

C – E If the voltage across the low pressure discharge tube is increased beyond point C, the current will rise exponentially. The electric field is now high enough so the electrons initially present in the gas can acquire enough energy before reaching the anode to ionize a neutral atom. As the electric field becomes even stronger, the secondary electron may also ionize another neutral atom leading to an avalanche of electron and ion production. The region of exponentially increasing current is called the ***Townsend discharge***.

D – E ***Corona discharges*** occur in Townsend dark discharges in regions of high electric field near sharp points, edges, or wires in gases prior to electrical breakdown. If the coronal cuurents are high enough, corona discharges can be technically "glow discharges", visible to the eye. For low currents, the entire corona is dark, as appropriate for the dark discharges. Related phenomena include the *silent electrical discharge*, an inaudible form of filamentary discharge, and the *brush discharge*, a luminous discharge in a non-uniform electric field where many corona discharges are active at the same time and form streamers through the gas.

E Electrical breakdown occurs in Townsend regime with the addition of secondary electrons emitted from the cathode due to ion or photon impact. At the breakdown, or sparking potential V_B, the current might increase by a factor of 10^4 to 10^8, and is usually limited only by the internal resistance of the power supply connected between the plates. If the internal resistance of the power supply is very high, the discharge tube cannot draw enough current to break down the gas, and the tube will remain in the corona regime with small corona points or brush discharges being evident on the electrodes. If the internal resistance of the power supply is relatively low, then the gas will break down at the voltage V_B, and move into the normal glow discharge regime. The breakdown voltage for a particular gas and electrode material depends on the product of the pressure and the distance between the electrodes, pd, as expressed in Paschen's law (1889).

Glow Discharge

The glow discharge regime owes its name to the fact that the plasma is luminous. The gas glows because the electron energy and number density are high enough to generate visible light by excitation collisions. The applications of glow discharge include fluorescent lights, dc parallel-plate plasma reactors, "magnetron" discharges used for depositing thin films, and electro-bombardment plasma sources.

F – G After a discontinuous transition from E to F, the gas enters the ***normal glow*** region, in which the voltage is almost independent of the current over several orders of magnitude in the discharge current. The electrode current density is independent of the total current in this regime. This means that the plasma is in contact with only a small part of the cathode surface at low currents. As the current is increased from F to G, the fraction of the cathode occupied by the plasma increases, until plasma covers the entire cathode surface at point G.

G – H In the ***abnormal glow*** regime above point G, the voltage increases significantly with the increasing total current in order to force the cathode current density above its natural value and provide the desired current. Starting at point G and moving to the left, a form of hysteresis is observed in the voltage-current characteristic. The discharge maintains itself at considerably lower currents and current densities than at point F and only then makes a transition back to Townsend regime.

Arc Discharges

H – K At point H, the electrodes become sufficiently hot that the cathode emits electrons thermionically. If the DC power supply has a sufficiently low internal resistance, the discharge will undergo a glow-to-arc transition, H-I. The ***arc regime***, from I through K is one where the discharge voltage decreases as the current increases, until large currents are achieved at point J, and after that the volateg increases slowly as the current increases.